THE BALTIC JOURNAL OF ROAD AND BRIDGE ENGINEERING
2024/19(4)

ISSN 1822-427X/eISSN 1822-4288
2024 Volume 19 Issue 4: 119–135
https://doi.org/10.7250/bjrbe.2024-19.651

ASSESSMENT OF THE ROAD ECOSYSTEM FOR AUTONOMOUS VEHICLES

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Received 31 June 2024; accepted 03 November 2024

Abstract. The rapid advancement of autonomous vehicle (AV) technology heralds a transformative era in mobility, promising to redefine transportation with enhanced efficiency, safety, and sustainability. Realizing this potential necessitates road ecosystem that fosters seamless interactions between AVs, infrastructure, and societal elements. This article assesses road ecosystem criterion groups tailored for AVs, encompassing critical components for their seamless operation. It addresses physical and digital infrastructure, communications, social environment and road users, and legal and economic environments. Integrating these diverse criterion groups creates a holistic framework supporting AV deployment and operation. By assessing the interplay

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between these groups, the study highlights the most important areas that facilitate seamless AV integration. The analysis examines the importance of current infrastructure for AVs, the effectiveness of communication systems, and the impact of social environment and road users, alongside the regulatory and economic conditions necessary for AV adoption. This article underscores the critical need for a multidisciplinary approach in shaping the future of transportation, paving the way for a seamless and sustainable transition into the era of autonomous mobility.

Keywords: autonomous vehicles, communication system, infrastructure adaptation, Kendall method, road ecosystem, road infrastructure.

Introduction

The rapid evolution of autonomous vehicles (AVs) is driving a profound transformation within the transportation sector, thereby introducing a new era of mobility characterised by enhanced safety, efficiency, and convenience. This shift necessitates a thorough evaluation of the road ecosystem to ensure the smooth integration of AVs into the current infrastructure. The ecosystem for AVs includes various components such as road infrastructure, communication systems, regulatory frameworks, and the interaction between AVs and other road users. Consequently, the incorporation of AVs into the transportation framework stands as one of the most transformative technological advancements of the 21st century, with the potential to revolutionise urban landscapes, increase safety, and boost overall efficiency. Notably, in 2023, the European Commission introduced a comprehensive regulatory framework to facilitate the deployment of autonomous vehicles across the EU (Sobiech et al., 2024). This framework emphasises the importance of safety, technological innovation, and cross-border cooperation, thus marking a significant step towards the integration of AVs in European transportation systems.

The successful deployment of AVs relies heavily on the robustness of existing infrastructure, including roads, traffic signals, and signage, which must be adapted to meet the specific requirements of AVs. Kondratovič and co-authors emphasize that this process involves not only physical enhancements but also the integration of smart technologies capable of communicating with AVs to provide real-time data, thereby improving safety and efficiency (Kondratovič et al., 2023a). Consequently, adapting current road systems is vital to meet the unique needs of AVs. Similarly, Gouda and other researchers indicate the importance of optimising road elements such as signage and road markings for AV detection and navigation, stressing the role these components play in the reliable functioning of AVs (Gouda et al., 2021). High-definition lane markings and adaptive traffic signals are particularly beneficial for AV navigation. Goodall states that infrastructure supporting AV technology enhances both safety and the efficiency of the transportation network (Goodall, 2014). Upgrading and maintaining road infrastructure for AVs is crucial to achieving efficient shared autonomous electric mobility, which can significantly improve both user experience and operating profits (Wang et al., 2024).

The deployment of AVs requires substantial changes to both physical and digital infrastructure. Digital infrastructure, which encompasses high-speed communication networks, cloud computing, and data centres, supports the real-time data exchange between AVs and their environment. As highlighted by Fagnant and Kockelman, the integration of AVs into the existing transportation system necessitates a robust digital infrastructure capable of handling the high volume of data generated by these vehicles (Fagnant & Kockelman, 2015). Moreover, an open approach to developing AVs, as proposed by Japan researchers, emphasises the use of commodity vehicles and sensors, along with algorithms, software libraries, and datasets for scene recognition, path planning, and vehicle control (Kato et al., 2015). This open approach allows researchers and developers to design new algorithms and test their performance, thereby facilitating advancements in AV technology.

Communication systems are crucial for the effective operation of AVs. Interaction between AVs and infrastructure is highly dependent on real-time data exchange, which can only be ensured through proper communications. Recent studies underline the significance of these systems in various ways. For instance, Liu and other researchers emphasise the integration of computing technologies and communication mechanisms like dedicated short-range communication, cellular vehicle-to-everything (C-V2X), and 5G, which are crucial for AVs to make reliable real-time decisions (Liu et al., 2020). The complexities of real traffic environments necessitate advanced computing systems to handle data from multiple sensors effectively. Furthermore, Chinese researchers propose a sensing and communication integrated system based on 5G technology to enhance the safety of AVs, ensuring low-latency and high data rate information sharing among vehicles, which is essential for preventing collisions and improving driving safety (Zhang et al., 2020). Pakistani researchers provide a comprehensive review of the integration of wireless technologies and sensor fusion for next-generation connected and autonomous vehicles, highlighting the importance of a robust communication infrastructure for timely and reliable data transmission to support AV decision-making processes (Butt et al., 2022).

Based on a research article by Palevičius and co-authors, the efficient development of travel is contingent upon the advancement of Intelligent

Transport Systems (ITS) and Cooperative Intelligent Transport Systems (C-ITS) (Palevičius et al., 2020). They state that cities integrating advanced ITS and C-ITS will experience improved AV performance and safety. These systems enable AVs to communicate with each other and with traffic management systems, facilitating coordinated movements and reducing traffic congestion. Moreover, digital infrastructure includes vehicle-to-everything (V2X) communication systems, which facilitate interactions between AVs and various elements of the road ecosystem. V2X communication is integral for cooperative driving, traffic management, and collision avoidance.

The integration of AVs within the existing traffic ecosystem must consider the interactions between AVs and vulnerable road users (VRUs), such as private vehicles, pedestrians, cyclists, and motorcyclists. Ensuring the safety of VRUs is critical for public acceptance and the successful deployment of AV technology. AVs must be equipped with advanced sensors and algorithms to detect and respond to VRUs, ensuring that their presence on the road does not compromise safety (Reyes-Muñoz & Ibáñez, 2022). The performance analysis of one-level signalized urban intersections with exclusive pedestrian phases and diagonal crossings, as studied by Grigonis and co-authors, provides insights into how AVs can navigate complex urban environments safely and efficiently (Grigonis et al., 2023). This analysis highlights the need for AVs to adapt to various traffic signal patterns and pedestrian behaviors, ensuring the safety of all road users.

Regulatory and economic conditions significantly influence the pace and extent of AV adoption. Governments and regulatory bodies must establish clear guidelines that address safety standards, liability, and data privacy. As emphasised by Gasser and Westhoff, robust regulatory frameworks are necessary to address the ethical and legal implications of AV technology (Gasser & Westhoff, 2012). Furthermore, economic incentives, such as subsidies for infrastructure development and tax breaks for AV manufacturers, can drive the growth of the AV market. Moreover, the participation of pilot self-driving vehicles intended for the carriage of goods, as assessed by Kondratovič and other researchers, illustrates the economic potential of AVs in logistics and freight transport (Kondratovič et al., 2023b). This study highlights the importance of regulatory frameworks and economic incentives to facilitate the integration of AVs into commercial operations, thereby enhancing the efficiency of goods transportation. Policies and regulations must be updated to address the unique challenges posed by AVs, such as liability in the event of an accident and data privacy concerns.

The development and maintenance of the necessary infrastructure, as well as the cost of AV technology, can pose financial challenges.

However, the long-term economic benefits of AVs, such as reduced transportation costs, improved productivity, and lower accident rates, can outweigh these initial investments. A study by American and British researchers suggests that the widespread adoption of AVs can lead to significant economic gains by enhancing the efficiency of the transportation system and reducing the societal costs associated with traffic accidents (Wadud et al., 2016). For example, Szűcs and Hézer highlighted that AVs have the potential to increase road safety significantly, reducing traffic accidents and related costs by minimising human error (Szűcs & Hézer, 2022). Similarly, research by Cui and co-authors emphasises the reduction in road accidents due to the ability of AVs to manoeuvre optimally, thereby addressing human errors that are a primary cause of accidents (Cui et al., 2019).

A highly cited study by Litman demonstrates that AVs can significantly reduce transportation costs by enhancing fuel efficiency, reducing labour costs for drivers, and minimising the need for parking infrastructure (Litman, 2018). Additionally, AVs are expected to foster the growth of new business models, such as shared mobility services, which can lead to significant cost savings for users.

Integrating the diverse criterion groups into a holistic framework is essential for supporting AV deployment and operation. This involves creating an ecosystem where AVs can seamlessly interact with physical and digital infrastructure, other road users, and regulatory frameworks. The World Economic Forum (WEF) has emphasised the need for a coordinated approach, stating that a holistic framework that integrates all aspects of the road ecosystem is crucial for the successful deployment of AVs (WEF, 2021). This includes developing standards for interoperability, ensuring that different AV systems can communicate and work together effectively.

Recent studies on the impact of AVs on climate change have provided insights into their potential to contribute positively to environmental sustainability. AVs can significantly improve fuel efficiency through optimised driving patterns, such as smoother acceleration and deceleration. For instance, research by Saudi Arabian researchers indicates that eco-driving and platooning could reduce greenhouse gas (GHG) emissions by up to 35% (Massar et al., 2021). Furthermore, the shift towards electric vehicles (EVs) is enhanced by the widespread adoption of AVs, which can lead to more efficient ride-sharing models. Consequently, this reduces overall vehicle miles travelled (VMT) and, in turn, emissions. This effect is corroborated by research from Jones and Leibowicz, who found that shared autonomous vehicles (SAVs) could lower both costs and emissions significantly, even if they induce double the VMT of the vehicles they replace (Jones & Leibowicz, 2019).

However, one of the less discussed aspects is the additional energy consumption and emissions associated with AV data management. American researchers highlighted that the storage and transfer of data for AV operations could result in emissions equivalent to adding over 5 million vehicles by 2030 (Hardaway et al., 2022). Therefore, while AVs present numerous opportunities for reducing emissions, challenges related to data management must also be addressed to fully realise their environmental benefits. Moreover, studies like that of Greenblatt and Saxena emphasise that AVs can support climate change mitigation by enabling more effective integration of renewable energy sources into the transportation sector. Their research indicates that AVs can help balance energy loads by aligning charging schedules with periods of low renewable energy demand, thus optimising the use of solar and wind power (Greenblatt & Saxena, 2015).

The seamless integration of AVs into the transportation ecosystem requires a coordinated and multidisciplinary approach. By addressing the key areas of physical and digital infrastructure, communication systems, social environment and road user interactions, and regulatory and economic conditions, a holistic framework can be developed to support AV deployment and operation. This will pave the way for a seamless and sustainable transition into the era of autonomous mobility, enhancing transportation efficiency, safety, and sustainability.

The assessment of the road ecosystem for AVs is a multifaceted endeavour that encompasses infrastructure upgrades, advanced communication systems, robust regulatory frameworks, and the nuanced interaction between AVs and other road users. As the technology continues to evolve, a proactive and comprehensive approach is essential to facilitate the seamless integration of AVs into the transportation network. By addressing these key aspects, we can unlock the full potential of AVs, paving the way for a safer, more efficient, and sustainable future of mobility.

Literature review has shown that autonomous transport can help address most of the challenges facing today's road transport system. Many countries are looking for the best solutions and measures to reduce the number of traffic accidents to achieve "Vision zero" goals. The European Union's road safety goals for 2030, as part of the "Vision Zero" initiative, aim to reduce road traffic deaths and serious injuries by 50% compared to 2020 levels (European Commission, 2019a). The fight against climate change is also aimed at reducing pollution in the road sector. The European Union aims to cut greenhouse gas emissions from transport by 55% compared to 1990 levels by 2030 (European Commission, 2019b). The initiatives include transitioning to clean and sustainable mobility solutions, such as promoting electric vehicles, enhancing public transport, and improving infrastructure to support greener transportation systems. There is a search for traffic management solutions that will allow people to travel without traffic jams or other disruptions, thus saving time on the road.

The predicted and explored benefits of autonomous transport are driving researchers and car manufacturers forward in the development of technologies and in the improvement of the different parts of the autonomous transport ecosystem. While many studies explore individual technological advancements, this research adopts a holistic approach, aiming to uncover the interdependencies between these criteria groups and their relative importance in advancing AV technologies. The aims of this research are to identify the main groups of criteria in the autonomous transport ecosystem that have the greatest impact on the development of the technology, to carry out an expert evaluation of the main groups of criteria and to calculate the weights of these groups using the Kendall method in order to find out the priorities for the development of the autonomous transport. The results provide new insights into which areas should be prioritised to accelerate the development and successful integration of autonomous transport. Additionally, the research moves beyond theoretical discussions by involving expert evaluations, thus providing a data-driven framework for future research and development efforts. This approach introduces a new perspective on AV ecosystem priorities by systematically assessing the complex interdependencies between infrastructure, technology, and communication systems, ensuring that future developments target the most impactful areas.

1. Establishment and evaluation of the list of the main groups of criteria

1.1. Compilation of the list of the main groups of criteria

The authors have identified the main groups of criteria for the road ecosystem and their possible components, based on a review and expert analysis of published international research articles. The authors have decided to assess and identify the impact of several ecosystem main criteria groups on the development of AVs in this research. The list of six main groups of criteria was presented to experts for evaluation, asking them to determine the significance of the groups with points. Future research articles will address the influence of the individual components of each group on the performance of autonomous transport and the significance of interactions between them. The selected groups of main criteria and the list of their components are presented in Figure 1.

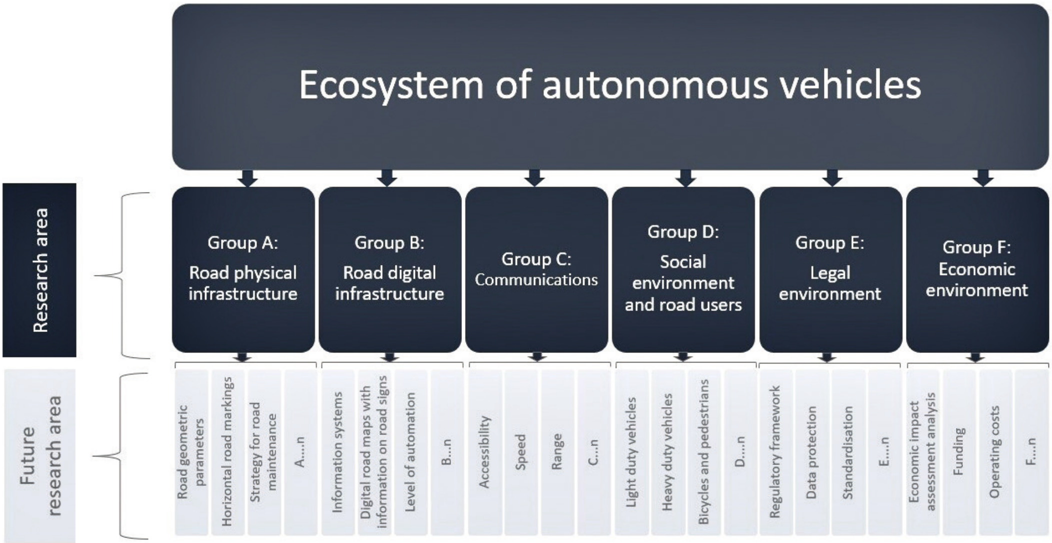

Figure 1. Main criteria groups for the autonomous vehicle ecosystem

Group A (Q1). Road physical infrastructure. The physical infrastructure of roads includes the essential components and facilities needed for safe and efficient transport. Currently, pavement surfaces, lane markings, signage, and traffic signals are primarily designed for human drivers. However, the rise of AVs necessitates improvements to these elements to meet the needs of intelligent driving systems. High-quality pavement surfaces are crucial for accurate sensor readings and vehicle stability, as irregularities in the pavement can disrupt sensor functionality and pose safety risks. Similarly, clear and consistent lane markings are vital for AV lane-keeping algorithms, which depend on their visibility and consistency. In the future, road infrastructure will need to incorporate advanced technologies. Smart intersections with integrated sensors and communication technologies will be critical for AV deployment. Regular maintenance of these infrastructure parameters, such as pavement quality and signage clarity will be essential to ensure reliable and safe AV operations. Transitioning to a road ecosystem that fully supports AVs requires significant enhancements in these infrastructure characteristics, including advanced materials, designs, and integrated systems, to facilitate seamless and safe AV operation.

Group B (Q2). Road digital infrastructure. Road digital infrastructure is essential for the successful deployment and operation of AVs, integrating technologies and systems that enable real-time communication, data exchange, and precise navigation, which are essential for higher levels of vehicle automation. This infrastructure includes a network of sensors, cameras, communication devices, and data processing systems embedded within the road network. In developed urban areas, traffic signals and road signs are increasingly equipped with sensors that communicate with AVs to enhance navigation and safety. However, rural or less developed areas often lack such infrastructure, limiting ability to achieve higher levels of automation and posing challenges for widespread AV adoption. To support full automation, advanced technologies such as smart intersections and dynamic traffic management systems, utilising AI and machine learning, will be necessary to analyse traffic patterns and make real-time adjustments to traffic signals and signage. High-definition mapping and precise geolocation technologies will provide AVs with detailed and accurate information about road geometry, traffic regulations, and environmental conditions.

Group C (Q3). Communications. Communications are crucial for AVs, facilitating data exchange between vehicles, infrastructure, and traffic management systems. Current technologies include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) systems, relying on dedicated short-range communications and cellular networks to enhance safety and efficiency. However, coverage and reliability can vary, especially in rural areas. The implementation of 5G networks continuously improve these systems with higher bandwidth, lower latency, and more reliable connections. Future communications will be even more critical, with 5G enabling instantaneous data exchange and sophisticated interactions. Advanced cybersecurity measures will be essential to protect against data breaches and malicious attacks. AI and machine learning will further enhance communications, allowing predictive analytics and adaptive responses to traffic conditions, improving overall traffic management.

Group D (Q4). Social environment and road users. The integration of AVs into the road ecosystem impacts various road users, including pedestrians, cyclists, light-duty vehicles, and heavy-duty vehicles, and is influenced by the broader social environment. Social factors, including public trust in technology, behaviour patterns, and cultural norms, influence how AVs interact with human-driven vehicles and other road users. Currently, a mix of human-driven and autonomous vehicles introduces new dynamics, requiring AVs to replicate human visual and social cues to avoid misunderstandings and accidents. Light-duty vehicles engage in complex manoeuvres, and AVs must safely interact with heavy-duty vehicles, considering their operational differences. Future widespread AV adoption is expected to enhance traffic flow and safety by reducing human error, but it will require significant infrastructure changes and continuous public education as the social environment adapts to new driving norms and the evolving role of AVs in daily transport to ensure a smooth transition.

Group E (Q5). Legal environment. The legal environment for AVs includes regulations, policies, and frameworks governing their operation, safety standards, and liability. The current legal landscape is evolving, with various regions adopting different regulatory approaches. Experts highlight that liability is a major concern, challenging traditional concepts of driver responsibility, as AVs make their own decisions. Future legal frameworks will need to address complex issues like the ethical implications of AV decision-making and how AVs prioritise safety in unavoidable collisions. International harmonisation of regulations is crucial, as AVs will operate across borders. Privacy and data security are also essential, requiring regulations to ensure data protection and responsible use.

Group F (Q6). Economic environment. The economic environment for AV technology involves significant financial implications, market dynamics, and policies influencing its growth. Currently, substantial investments by private companies and public institutions focus on R&D, infrastructure upgrades, and supportive regulatory frameworks. Leading companies like Tesla, Waymo, and Uber drive innovation in this field. The economic benefits of AVs are considerable, including reduced operational costs for transportation companies by minimising the need for human drivers and improving fuel efficiency through optimised driving patterns. This leads to cost savings and environmental benefits. Future widespread adoption of AVs could transform the economy, creating new industries and job opportunities in tech development, infrastructure maintenance, and cybersecurity. However, this shift may also lead to job losses in traditional driving roles and require significant infrastructure investments.

1.2. Assessment of the main criteria groups using Kendall method

The experts were selected for the assessment of the main criteria groups based on their work experience (no less than five years), position at their workplace (division level and higher) and academic degrees (Master degree and higher) in fields related to the research. The expert group consisted of experts from Lithuania (specialising in innovation, intelligent transport systems, communications, autonomous vehicle legislation and policy making) and Polish experts. A total of twenty-seven questionnaires were sent out for expert evaluation, describing in detail the main groups of criteria identified by the authors.

The Kendall method was used for the evaluation, according to which the criteria groups were ranked on a scale of one to six. A total of 27 questionnaires were completed and their data used for the evaluation.

Individually interviewed experts (hereafter referred to as E1–E27) provided their assessments of the importance of the main groups of criteria (hereafter referred to as Q1–Q6) for AV ecosystem, using their personal expertise, experience, qualifications, and intuition. These assessments are presented in Table 1. The evaluation values for each group were determined using a 6-point scale. If the evaluated component is deemed the least important for AV traffic, then it is assigned 6 points, and if the component is considered the most important, it is assigned 1 point, with the points for the other components allocated accordingly.

The Kendall method is a suitable statistical tool for analysing the level of agreement among experts in assessments or rankings. Kendall first introduced this method to calculate the correlation coefficient to determine whether two experts agreed in their opinions (Kendall, 1970). Later, Kendall and Gibbons expanded on its application in further studies (Kendall & Gibbons, 1990). However, when the number of experts is higher, the concordance coefficient W is used to evaluate the overall agreement among a group of experts. Zavadskas, Peldschus, and Kaklauskas discuss the application of Kendall's W, highlighting its role in maintaining the consistency of expert rankings in larger-scale assessments (Zavadskas et al., 1994). In a later study, Zavadskas and Vilutienė also emphasise the effectiveness of Kendall's W in similar contexts (Zavadskas & Vilutienė, 2006). Palevičius and his co-authors highlight the suitability of Kendall's W for evaluating expert consensus, particularly in multi-criteria decision-making (Palevičius et al., 2019). Similarly, Ginevicius supports the method, emphasising its adaptability to practical applications in contemporary settings (Ginevicius, 2011). Both works reflect the versatility of Kendall's W across various fields. As Kendall method is designed for ordinal data, it is an ideal choice for the present analysis. This method is logical and easily applicable in practical calculations (Jakimavičius et al., 2016).

Table 1. Ranks of the groups of criteria assigned by each expert

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20	E21	E22	E23	E24	E25	E26	E27
Q1	6	4	3	4	5	4	4	1	2	1	1	3	4	2	1	1	3	2	5	3	1	4	1	2	1	1	3
Q2	1	3	5	1	6	3	3	2	1	2	3	1	1	4	3	3	1	3	1	1	3	2	3	1	4	2	1
Q3	4	2	6	3	3	2	2	3	5	3	4	2	2	3	2	2	4	5	2	4	2	3	4	3	5	4	2
Q4	3	5	4	6	1	5	5	4	3	5	5	5	3	5	5	4	2	1	4	2	5	5	5	5	2	6	4
Q5	2	1	2	2	2	1	1	5	4	4	2	4	5	1	4	6	5	6	6	5	4	1	2	4	3	3	5
Q6	5	6	1	5	4	6	6	6	6	6	6	6	6	6	6	5	6	4	3	6	6	6	6	6	6	5	6

Kendall concordance coefficient is linked with the sum of rank of each factor R_j and with regard to experts:

$$R_j = \sum_{i=1}^{n} R_{ij},\ j = 1, 2, \ldots, m. \tag{1}$$

The mean rank of each factor $\overline{R}$ is obtained dividing the sum of ranks assigned thereto by number of factors:

$$\overline{R} = \frac{\sum_{j=1}^{m} R_j}{m}, \tag{2}$$

where R_{ij} – the rank given by expert i to factor j; n – the number of experts (i = 1, 2, ..., n); m – the number of factors (j = 1, 2, ..., m).

The difference between sum $\sum_{i=1}^{n} R_{ij}$ of ranks R_{ij} and constant quantity 1/2 n(m + 1) is calculated for each criterion:

$$\sum_{i=1}^{n} R_{ij} - \frac{n(m+1)}{2}. \tag{3}$$

The square of the difference between ranks' sum $\sum_{i=1}^{n} R_{ij}$ and constant quantity 1/2 n(m + 1) is calculated:

$$\left[\sum_{i=1}^{n} R_{ij} - \frac{1}{2} n(m+1)\right]^2. \tag{4}$$

Upon calculation as per Equations (1)–(4), the next step is to calculate the concordance coefficient W:

$$W = \frac{12S}{n^2(m^3 - m)}. \tag{5}$$

Significance of concordance coefficient and compatibility of expert evaluation of factor groups is determined by χ^2:

$$\chi^2 = \frac{12S}{nm(m+1)}. \tag{6}$$

Min value of the concordance coefficient $W_{\min}$ is calculated using Equation (7):

$$W_{\min} = \frac{\chi^2_{v,\alpha}}{n(m-1)}. \tag{7}$$

where $\chi^2_{v,\alpha}$ – Pearson critical statistics, which value is found in the table (Montgomery, 2009), taking the degree of freedom v = m – 1 and significance level α.

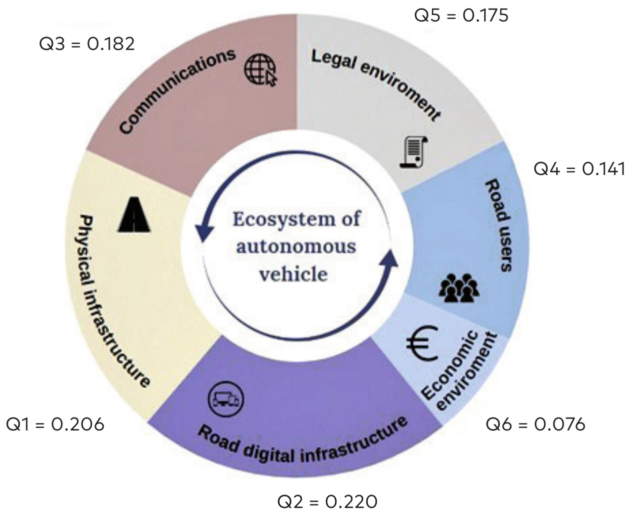

Figure 2. Determined weights for each group of criteria

The survey conducted among 27 experts revealed that the most crucial group of criteria in the AV ecosystem was road digital infrastructure (0.221). Road physical infrastructure ranked second in terms of importance (0.206), followed by communications (0.182). The weights of all groups of criteria are illustrated in Figure 2.

Conclusions

The successful deployment and integration of AVs into the transportation ecosystem hinge on a well-coordinated approach that addresses multiple interrelated criteria groups. By applying the Kendall method, the most impactful components have been determined and their relative importance has been established through expert evaluations. This data-driven approach reveals the interdependencies between these elements, offering clear priorities for future technological development and ensuring targeted improvements that will drive the advancement of autonomous transport. The findings from this survey highlight the critical areas of focus, including the enhancement of digital and physical infrastructure, the development of robust communication systems.

The survey conducted among 27 experts has provided a comprehensive overview of the key criteria groups within the AV ecosystem, shedding light on their relative importance and interrelationships. The findings reveal critical insights that can guide future development aimed at facilitating the seamless integration of AVs into the transportation system. The analysis reveals the intricate interdependencies among different criteria groups within the road ecosystem affecting AV development.

Calculations using the Kendall method have highlighted:

- Dominance of road digital infrastructure: the survey results indicate that road digital infrastructure has been rated as the most important criterion (0.221). This suggests the need for a robust digital framework, enabling AVs to navigate complex environments and respond to real-time traffic conditions effectively.
- Significance of road physical infrastructure: road physical infrastructure ranked second (0.206), emphasising the need for well-maintained roads, clear signage etc. These elements are essential for AVs to effectively detect and navigate their surroundings.
- Role of communications: communications infrastructure, identified as the third most important criterion group (0.182), is vital for the effective operation of AVs. Effective communication systems facilitate interaction between AVs and various elements of the road ecosystem, including other vehicles, traffic signals, and management systems.

Future research should include an in-depth analysis of sub-groups to investigate specific sub-criteria within the main criterion groups to determine which elements are most impactful. This will ensure that development efforts are targeted and effective, paving the way for a seamless and sustainable transition into the era of autonomous mobility.

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